Part I

CLOSED TELEVISION SYSTEMS

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CHAPTER 1

TRANSMISSION OF PICTURES

1-1. Definitions

Television has been defined as the electrical transmission of a succession of images and their reception in such a way as to give a substantially continuous reproduction of the subject or scene before the eye of a distant observer. Any complete electrical network that meets these requirements is termed a television system and its function is to generate, transmit, and reproduce video or picture information. Since the information to be conveyed is not electrical in nature, the network must have at least three basic elements: first, a transducer that serves to convert the optical data into some sort of equivalent electrical signal; second, an electrical link to carry these signals to a distant point; and third, another transducer that reconverts the electrical signals into an optical image which is acceptable to an observer at the distant point. These three elements are directly related to the threefold function of the television system stated above: a transducer to generate, a link to transmit, and a transducer to reproduce the desired information.

What additional components are required over and above these three depends largely upon the character of the information, the speed of transmission, and the characteristics of the transmission medium. Thus, if an intelligent engineering approach to the subject of television systems is to be taken, we must first look to the nature of the information which the system must handle.

The foregoing statements are more or less applicable to any electrical communications network which is to transmit information that is nonelectrical in itself. For example, in the transmission of speech by telephone, microphone and receiver serve as transducers with the connecting link furnished by wires. The additional elements of the telephone system—such as repeating amplifiers, modulators, filters and detectors in a carrier system—depend on the wire transmission characteristics, the time allowed for transmitting a given amount of

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information, and the very nature of speech itself. In order to design transducers and other components that will give a satisfactory reproduction of the speech input, the engineer must first know the characteristics of the signals with which he is dealing. Hence, in our approach to the elements of television systems we start first with a brief analysis of a picture and the problems of transmitting such a picture over an electrical communication channel. From this we may proceed to a study of transducers and their associated equipment which will provide an electrical signal acceptable to the channel. The various components may then be joined into typical television systems.

Throughout this entire procedure we must remember that practical picture transmission involves the production of the illusion of a complete picture for the distant observer and that the function of the television engineer is to design, build, and maintain a commercially feasible system which will accomplish this illusion.

1–2. A Matter of Dimensions

Since the transmission of picture information is to take place over an electrical link of some sort, it seems desirable to see if such a link imposes any broad limitations on the type of signals which it can convey.

By definition, the response of an electrical circuit is a single-valued function of time. By this we mean that if signals from a number of sources are applied to the input terminals of a four-terminal network, they will add in such a manner that the voltage at the output terminals will have one, and only one, value at any instant of time. Whereas it is true that the output signal over a period of time may be resolved into separate frequency components, still it has only one amplitude instantaneously. We might say, then, that an electrical link is limited in that it may accommodate only a single-valued function of time. As an illustration of this principle we may consider the network shown in Fig. 1–1. An external noise source introduces a component of current $i_N(f,t)$, which adds to the signal current $i_S(f,t)$. A current $[i_S(f,t) + i_N(f,t)]$ which has only one amplitude at any instant will be delivered to the receiver. It would seem, therefore, that a communication channel is limited in the type of signal it can handle; all components will add to give a single-amplitude function of time.

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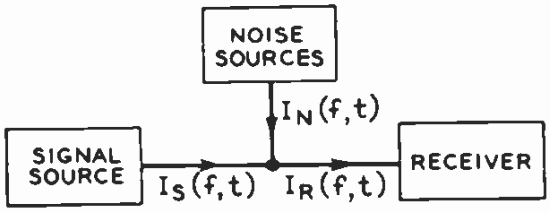

Fig. 1–1. Signal and noise combine to give a single-valued function of time.

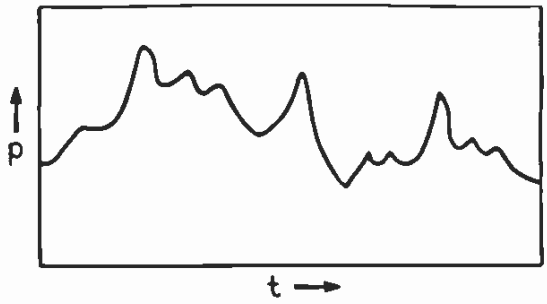

Fig. 1–2. Sound pressure is a single-valued function of time.

Fortunately for the communication art most forms of intelligence that are transmitted by electrical means are either inherently single-valued or may be forced into a single-valued form. Speech is an example of the first type because the spoken message may be represented at any point in space by a plot of sound pressure against time. This is illustrated in Fig. 1–2. If a suitable microphone is placed at that point, the variations in pressure would be converted into corresponding variations in voltage or current, and, in the absence of distortion, the electrical signal would also appear as in Fig. 1–2 but with the pressure scale replaced by voltage or current. Thus in the transmission of speech by wire—and the discussion may be extended to include radio communication—the entire message may be represented by a single-valued function of time.

Turning to the problem at hand, we have an example of the second type of intelligence. Let us consider that a picture or photograph of some sort is to be transmitted and, further, let us try to handle picture transmission in the same manner as speech. In place of a microphone a phototube is used as a transducer. If the light from the photograph is focused onto the phototube, an electrical current will be developed which once again is a single-valued function of time, but notice that all detail of the image is lost in the electrical signal. Since the phototube "sees" the entire image, the best it can do is to develop a signal that is proportional to the average brightness of the image. It has no way of recognizing that the picture is in fact a bounded, two-dimensional continuum of brightness. We might say that there is a complete incompatibility between the information to be transmitted, which is inherently two-dimensional, and the electrical system, which is only capable of handling a one-dimensional signal.

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This basic incompatibility may be resolved, however, by a compromise. Experience with photographs and half-tone printing methods has shown that as a result of the limited acuity of the eye a perfectly satisfactory picture results if the continuum of brightness is replaced by a field of elemental areas, the brightness of each being the average brightness of the corresponding area in the original image. This concept is illustrated in Fig. 1–3, where the actual variation in

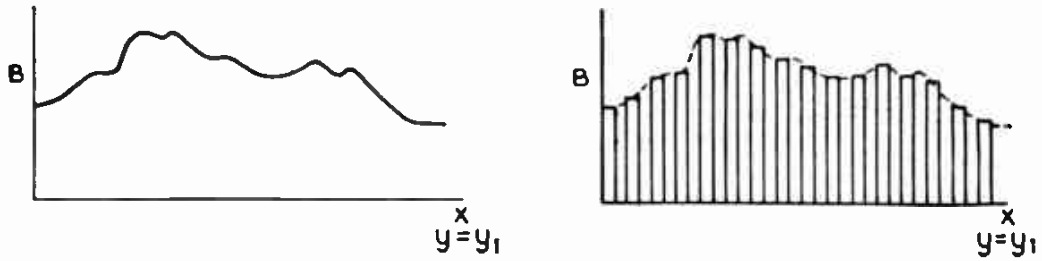

Fig. 1–3. The actual distribution of brightness is replaced by a number of samples.

brightness across the picture is replaced by a large number of samples of average brightness. If this process be extended in both dimensions over the picture, it may be seen that the original picture will be replaced by M smaller pictures, each of which is of constant brightness. M may be termed the "figure of merit" of the approximate picture, and the greater the number of samples, the closer will be the approximation of the original scene.

How this procedure is accomplished in an actual system will be described later. For the moment a simple system may be proposed. Let the picture be focused on a field of infinitesimally small phototubes, spaced closely together. Then the output of each phototube is proportional to the average brightness of an elemental area. Now

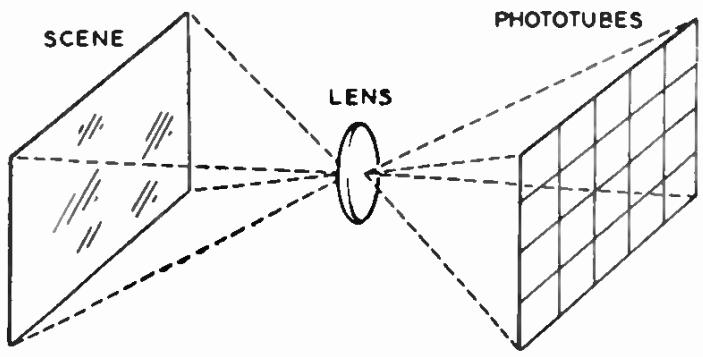

Fig. 1–4. The scene is focused onto an array of phototubes.

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if the information so derived is to be transmitted to some point over a wire system, for example, a reproducing system which will convert voltage to brightness is required, which further has a one-to-one correspondence to the phototubes in regard to both number and position.

Since the phototube for each picture element delivers the proper type of electrical signal for a communication channel, the entire picture may be transmitted by connecting the M phototubes to M reproducing elements so that signals from all the elements are transmitted simultaneously in parallel. Care must be taken that each pair of pickup and reproducing elements so connected occupy corresponding positions in the over-all picture field so that the space co-ordinates are restored. Whereas such a parallel transmission system as shown in Fig. 1–5 appears feasible on paper, its accomplish-

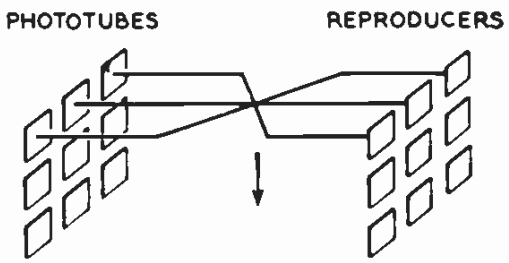

Fig. 1–5. Parallel transmission.

ment is practically out of question when it is realized that for a satisfactory picture some 100,000 elements and channels would be required. This number is determined by such factors as picture size and viewing distance, but 100,000 is a good round number to represent the order of magnitude of the problem posed by this parallel transmission system in which information from all M elements is transmitted simultaneously and over parallel communication channels.

One practical value of the parallel transmission system just described is that it illustrates the concept of sampling which is of great importance in picture transmission: one large area whose brightness varies from point to point may be replaced by M small areas or samples, the brightness of each being a sample of the brightness in the corresponding region of the original picture. The purpose of the sampling process is to render the bidimensional information amenable to transmission over M electrical systems.

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We must now find a means of reducing the number of channels. We have seen that the picture may be sampled in space. If now it be sampled in time as well, the problem is solved. Suppose that two rotating, sampling switches are introduced into the system as shown in Fig. 1-6. With this arrangement the phototube outputs are

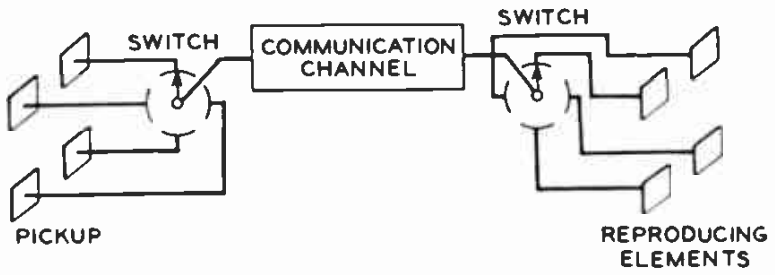

Fig. 1-6. Sequential transmission. Picture information from the several pickup elements is sampled in sequence.

sampled in an orderly fashion and a complete compatibility exists: the two-dimensional information has been reduced to a single-valued function of time. Nevertheless some sacrifice is made for the compromise. The original image has been resolved or broken up into M elements with a loss in resolution or detail, and the entire picture is never displayed in its entirety at any instant at the reproducer. This second fact requires that the sampling process occur at a rate sufficiently high that the eye may reassemble the picture and see its motion reproduced in a satisfactory manner.

This second or sequential system of picture transmission, in which the picture elements are sampled in time, forms the basis of modern television systems and, as such, needs closer examination. Consider the requirements on the three main components of the system.

Pickup System:

(1) Is a photoelectric transducer.

(2) Breaks the picture up into M samples or elements in space.

(3) Has a selecting mechanism that samples these elements in some orderly manner in time and delivers these samples in sequence to the communication channel.

Reproducing System:

(1) Is an electrophoto transducer.

(2) Has a selecting mechanism which, operating in exact synchronism with the pickup selector, delivers the time samples from the communication system to the proper playback elements so that each sample is restored to its proper position in space.

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Communication Channel:

(1) Must have the capabilities, i.e., bandwidth and delay characteristics, to deliver all signal and switch-synchronizing information furnished by the pickup system over the required distance to the reproducing system, and all this with a minimum of distortion.

Over a period of years considerable ingenuity has been used to develop devices which at the pickup end combine the functions of breaking up the picture into elements, selective switching, and converting light to voltage or current. Typical of these are the image dissector, the iconoscope, and the image orthicon. At the reproducing end the same functions have been combined into the cathode-ray tube, or CRT, which is used exclusively for direct-view television service and will be assumed as the reproducing transducer through the rest of this book.

The combined functions of breaking the scene up into elemental areas and switching them is termed "scanning." In the several devices mentioned above, scanning is accomplished by causing a beam of electrons to be deflected over either a suitable photoemissive surface for pickup or a fluorescent surface for reproducing.

1-3. Facsimile v. Television

Generally speaking there are two types of service in which picture information is transmitted: facsimile and television. In the former, a photographic image is delivered at the playback end, whereas in television an optical image must be presented which is suitable to the human eye. Because of this difference in display at the receiving end the actual details of the two systems differ considerably. Consider the problem in television. It has been stated before that the entire scanning process must proceed at a fast enough rate so that the eye can successfully integrate the samples which are displayed in sequence into a complete picture. The eye never sees a complete image of the picture, but only a small part of it at any given instant. The question arises, then, how fast must the entire picture area be covered by the scanning device? A number of factors are cogent, two of them being retina retentivity in the eye and, where phosphor-coated CRT's are used for display, the glow time of the phosphor. The former is a psychological phenomenon in which the eye "sees" an image for a short period after the stimulus is removed. It is this property of the eye which makes possible effective integration of all the information which has been presented in sequence.

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The second factor is a characteristic of all phosphors or fluorescent materials which after being bombarded by an electron stream, continue to glow with the intensity decreasing exponentially in time. The actual decay time from the removal of excitation until the intensity reaches the threshold of visibility may be controlled by proper composition of the fluorescent material being excited. In P4 screens of the type used for television service this decay time is in the order of a millisecond.[1] This short but finite glow period is of considerable aid to the eye in reassembling the entire picture from its many parts.

Another factor to be considered is that motion in the original televised scene must also be reproduced. This problem is shared in "moving" pictures in which a series of "still" photographs must be presented in rapid enough succession so that apparent motion results. The cinema industry has found that if the eye is presented at least 16 complete pictures per second, then the illusion of motion is satisfactory. This figure of 16 pictures per second also presents the sequential data to the eye rapidly enough so that not only motion but the entire television picture itself appears satisfactory to the eye. It will be seen later that flicker difficulties place further demands on the speed of picture presentation.

Summarizing, it is seen that the eye demands at least one picture in $\frac{1}{16}$ second. In facsimile service on the other hand, a photographic image is constructed and the demands on speed of presentation are much less stringent. In fact, 20 or more minutes may be utilized in the transmission, reception, and reproduction of a single still picture. Translated in terms of scanning requirements, this means that the scanning in facsimile work is extremely slow and mechanical means for moving some scanning element may be used. With this slight background, a facsimile system may be described which will illustrate the principal components required and the interrelationship between them.

1–4. A Facsimile System

It will be assumed that a high-quality photograph of a normal size of 7 in. by $8\frac{1}{2}$ in. is to be transmitted. If this is illuminated, the light reflected from its surface will contain information as to the

[1] I. G. Maloff and D. W. Epstein, "Luminescent Screens for Cathode Ray Tubes." *Electronics*, **10** (11), 31 (November 1937).

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brightness distribution over the picture area. This must be converted to electrical energy so that the first component required in the system is a photoelectric transducer. A phototube or photocell will serve in this capacity.

Secondly, means must be provided for the reduction of the picture into a number of elemental areas and for switching them to the communication channel in orderly sequence. In the previous discussion of sequential transmission an array of infinitesimally small phototubes plus a switch was proposed. In the interest of simplicity, however, assume that this multiplicity of stationary phototubes is replaced by a single phototube which scans across the image. By this simple expedient the two functions of breaking into elements and switching may be combined. In a typical type of facsimile equipment[2] the scanning phototube is fixed, and the copy is made to move in front of it, as shown in Fig. 1–7. In order that the photocell see only a small elemental area of the picture a special optical system is used. As may be seen from the diagram, light from an exciter lamp

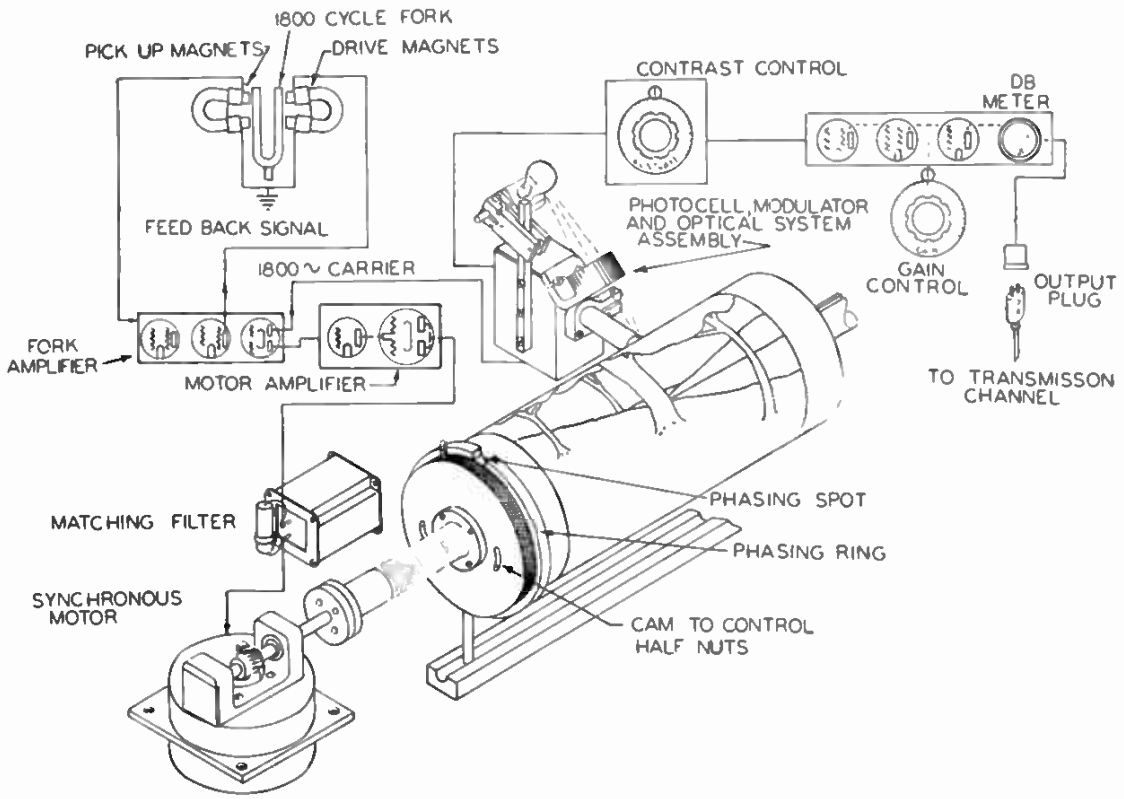

Fig. 1–7. The pickup equipment of a facsimile system. (Courtesy of Times Facsimile Corporation.)

[2] *Elements of Facsimile Communications*, The Times Facsimile Corporation.

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of constant intensity is focused onto the moving copy. The reflected light passes through a small defining aperture in the light-tight housing to the photocell. Ideally this aperture should be infinitesimally small since it determines the size of the picture elements and hence the detail in the final image. Practical considerations rule out this possibility, however, and the actual aperture size is about 0.01 in. square. We shall see in Chapter 5 that the finite size of this scanning aperture introduces distortion in the electrical signal and that the nature of the distortion is such that it may be corrected electrically.

Since the photocell provides the required conversion from light to voltage, we next consider the scanning means which move the picture area across the aperture. It may be seen in Fig. 1–7 that the copy is fixed on a drum that is keyed to a revolving lead screw. Thus when the synchronous motor operates, the copy drum revolves and moves along the lead screw. In this manner the entire copy is scanned. Speed control of the entire process is maintained by driving the synchronous motor from a stable-frequency tuning-fork oscillator. The output of the fork oscillator is also used as a carrier which is amplified and fed to the communication channel.

The inverse process must be carried out at the reproducing end of the system; that is, a similar scanning drum is required to restore the sampled information to its proper location in the image, and the electrical signal must be converted back to light so that it may expose the photosensitive paper which is wrapped around the receiving drum. The major portions of the reproducing system are shown in Fig. 1–8. The drum is driven at proper speed by a fork-controlled synchronous motor and the optical system consists of a focusing lens and a neon light whose luminous output is proportional to the incoming electrical signal. The final image is produced by developing the photographic image, which has been exposed on the revolving drum.

Now it can be seen that if the image is to be reproduced properly, both drums must rotate in synchronism. Since both motors will rotate at the same speed as a result of the action of the fork oscillators, it is only necessary that the two drums start scanning in phase. This is accomplished in the following manner: At the beginning of a transmission the reproducing drum is prevented from rotating by the clutch, stop arm, and trip magnet shown in Fig. 1–8. As the recording drum of Fig. 1–7 starts to rotate, the photocell scans the phasing spot and transmits a phasing pulse which is fed to the communication

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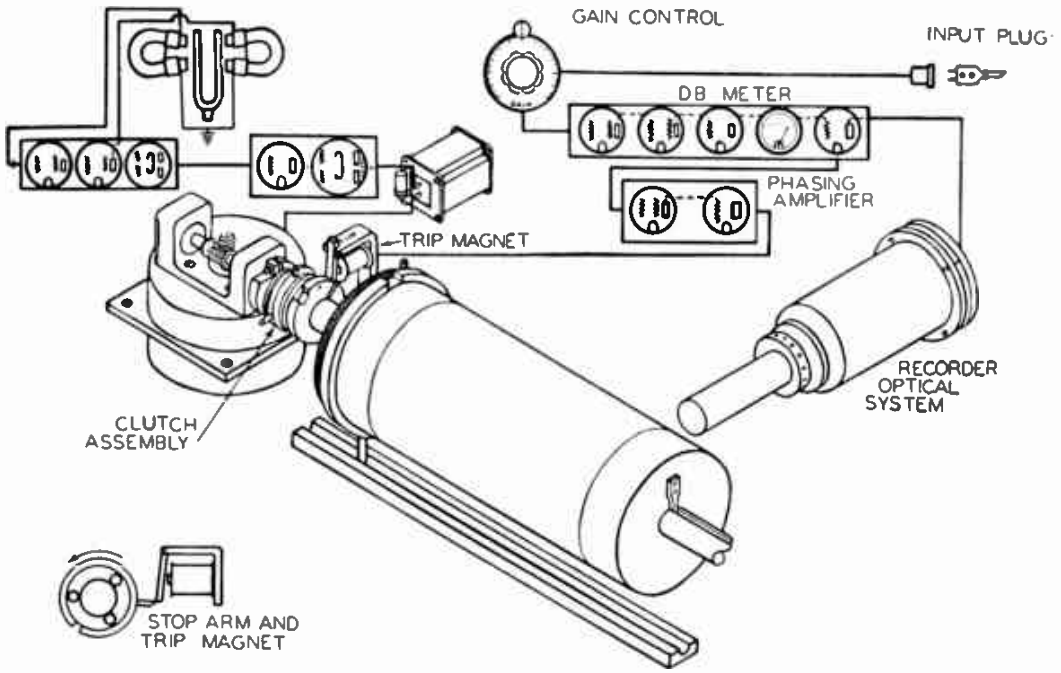

Fig. 1–8. The reproducing equipment of a facsimile system. (Courtesy of Times Facsimile Corporation.)

channel. When this pulse arrives at the receiving end, the trip magnet releases and the reproducing drum begins to revolve. As we have seen, the control afforded by the fork oscillators will hold the two drums in synchronism for the duration of the transmission.

Some idea of the performance of this facsimile equipment may be had from the following figures: With the two drums rotating at 90 revolutions per minute an image of 7-in. by $8\frac{1}{2}$-in. size may be transmitted in seven minutes within a 2000-cycle bandwidth. In more familiar terms, average typewriter copy may be transmitted at a rate of approximately 130 words per minute.

As we extend the ideas of picture transmission we shall see that, for a given amount of transmitted detail, bandwidth and time of transmission may be interchanged. We shall also see that in the television system a more complex system of synchronizing the pickup and reproducing scanning motions is required.

It would be desirable at this point to set up an analogous simple television system so that the requirements of the two types of service, facsimile and television, could be compared. It has been pointed out, however, that the scanning speeds required in television are so high that the use of some mechanical scanning system such as described

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above is precluded.[3] Recourse must be made to electronic scanning systems and a description of the all-electronic television system will be postponed until certain of its important components have been discussed.

These chief components are the pickup and display devices plus the units required to produce scanning in them. The over-all approach in the remainder of this book will be to describe, and where feasible, to set up design procedures for the various components required for a closed system comprising a single pickup assembly and a single reproducing assembly interconnected by wire. This simple type of system has many fields of application.[4] With the simple system completed, the problems of a commercial television broadcasting system will be considered. Here the problems are more complex, first because a large number of reproducing assemblies or receivers are associated with any given transmitter, and second because the wire link between sending and receiving ends is replaced by a radio communication system. These added complexities require considerable modifications in the simple closed system. The over-all treatment, then, is a progression from the specific to the more general.

In developing the closed system we shall follow a definite method of approach: In Chapter 2 we shall set up a number of standards which specify the pattern in which the image is scanned. In Chapter 3 we study the various means of producing the required scanning pattern and set up the wave forms of voltage required to cause an electron beam to follow the prescribed scanning pattern. With the scanning voltage specified we consider circuits for generating these voltages in Chapter 4. Next a study is made of the distortion introduced by the scanning process. The three remaining chapters take up the television camera tubes, the video amplifier circuits used for amplifying their output signals, and assemble these components into three basic types of closed television systems.

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[3] A notable exception to this statement is the Scophony system of scanning which has enjoyed some popularity in Great Britain. The post war trends in the United States, however, have been toward all-electronic scanning. See H. W. Lee, "The Scophony Television Receiver." *Nature*, **142**, 59 (July 9, 1938). *See also* Fig. 14–35.

[4] R. W. Sanders, "Industrial Television." *Radio and Television News* (Radio and Electronic Engineering Edition), **12**, No. 2, 3 (February 1949).

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CHAPTER 2

PICTURE STANDARDS

A successful communication system must have agreement between transmitter and receiver concerning how certain functions are to be performed. For example, in speech it is understood that sound is to be the common carrier and, except for the rare case of the lip reader, it is assumed by the message source that an ear, rather than an eye or nose, is to be the receiver. Once this agreement between transmitter and receiver has been reached, standards may be set up specifying how these various functions shall be performed. In the case of the various commercial broadcasting services where individual agreements between the tremendous number of transmitters and receivers would be impractical, the Government in the form of the Federal Communications Commission establishes and enforces the standards. The need for this standardization is particularly strong in telecasting services because of the so-called "lock and key" relationship between the two ends of the system; all receivers within the service area of a given transmitter must be able to receive and display its program material satisfactorily. On the other hand, in a simple closed wire-connected system involving only one transmitter and one receiver these standards may be held to the barest minimum.

In the discussion of standards, then, the elements requiring standardization fall into two broad categories: those pertaining to any system, closed or broadcasting, and those relating more specifically to commercial telecasting by radio. Those of the first group which have to do with the picture proper and the method by which it is scanned are the subject of this chapter.

In a closed system what factors must find agreement between the pickup and playback ends? Probably the most obvious answer is picture shape. Furthermore, if reference is made to the general requirements of scanning outlined in the last chapter, it will be seen that speed, geometry, and direction of scan must also be included.

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Other factors are the figure of merit or number of elemental areas used and the rate of picture transmission. These will now be considered.

2–1. Picture Shape

At first glance the choice of one picture shape from the infinite number of possible shapes is a difficult one. Practically speaking, however, the choice is quite limited because scanning problems require that the shape of the scanned area be some regular and simple geometric pattern. Thus the field of choice is narrowed on this basis to three shapes: the circle, the square, and the rectangle.

It has been stated previously that the most common display device in modern television is the cathode-ray tube. Since for constructional reasons these tubes are often built with circular viewing screens,[1] it seems reasonable to choose a circular picture shape, because then the entire fluorescent surface of the tube may be used for display of the picture. The following question must now be answered: Given a circular picture shape, can it be scanned in some relatively simple pattern? Two reasonable possibilities exist which are shown in Fig. 2–1. A set of closely spaced horizontal (or vertical) lines may be used. The solid lines indicate a "forward" trace; the dotted lines, a "reverse," retrace, or flyback path over which the electron beam returns to its pattern-starting point. For ease of scanning, picture data is presented on the forward trace only. During flyback, which is made as short as possible, the electron beam is blanked out to prevent contamination of the image display. Despite the circular tube shape all the scanning lines are shown of equal length in order to ease the requirements on the scanning generator.

From the viewpoint of utilizing as much as possible of the scanning time for picture presentation the horizontal linear scan of Fig. 2–1*a* is poor. On the other hand, it provides maximum utilization of the tube face. Notice that an alternative system would shrink the

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[1] Noncircular cathode-ray tubes have been built but they were not available commercially until the latter part of 1949. Tubes of this type were used by the Columbia Broadcasting System in receivers developed for their sequential color television system. These tubes had an end shape approximately rectangular with slightly rounded corners. *See*, for example, P. C. Goldmark, J. N. Dyer, E. R. Piore, and J. M. Hollywood, "Color Television" Part I. *Proc. IRE*, **30**, 4 (April 1942). *See also*, P. C. Goldmark and R. Serrell, "Color and Ultra-High-Frequency Television." *Proc. 1st National Electronics Conference*, 182 (October 1944).

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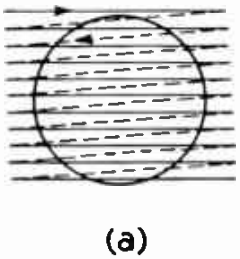
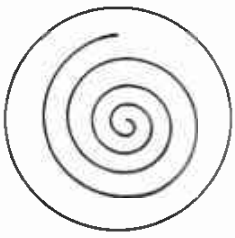


(a)



(b)

Fig. 2–1. Scanning a circular area. (a) Linear horizontal scan. (b) Spiral scan.

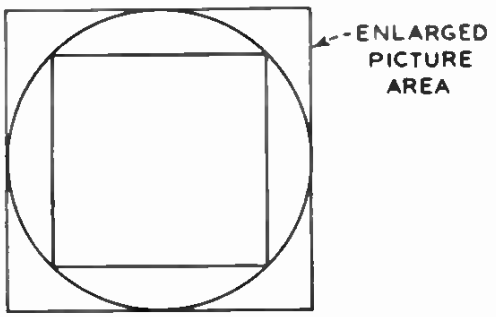


Fig. 2–2. An enlarged image may be obtained by expanding the sweep, but only with the loss of a large portion of the picture.

scanning pattern so that it lies entirely within the limits of the tube face, in which case all of the sweep time is utilized, but part of the fluorescent screen is lost. In effect, then, we may trade time utilization for space utilization. These two alternative schemes are illustrated in Fig. 2–2. It may be seen that the smaller scan results in a square or rectangular picture shape, which will be discussed later in this section.

We have just seen that the linear horizontal scan of a circular image is wasteful of large intervals of scanning time. Consider a second alternative, the spiral scan. Here the entire scan may be used for display. Hence it appears that the spiral scan is satisfactory on this basis. But other questions arise, such as: Can this scanning pattern be generated without too much difficulty, and what, if any, are its disadvantages?

In answer to the first question assume that a CRT employing electrostatic deflection is used. Figure 2–3 shows the circuit diagram of one type of circuit which will provide the necessary voltages to generate the spiral. In the diagram the center-tapped input transformer with R_1 and C_1 constitutes a phase shift network which feeds sinusoidal voltages in quadrature to the grids of V_1 and V_2. If, for the moment, the screen grids are held at a constant voltage, the amplified grid voltages will cause the electron beam to follow a circular path on the cathode-ray tube screen. If the screen voltages now be varied in a saw-tooth manner as shown in the diagram, the amplification of each stage will change with the screen voltage. This means that the electron beam follows a circular path of increasing radius or a spiral.

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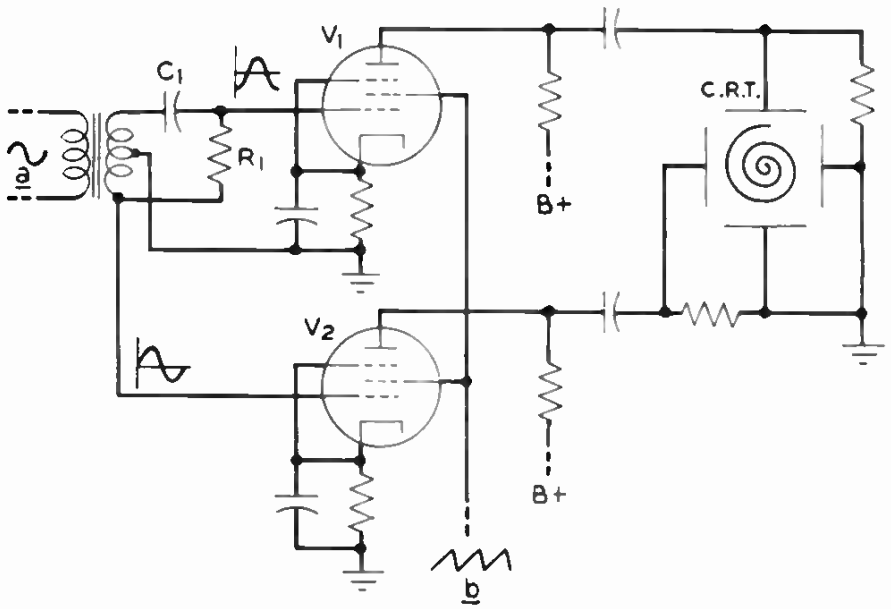

Fig. 2–3. Circuit for generating a spiral scan on an electrostatic deflection cathode-ray tube.

The number of revolutions in the complete spiral is determined by the relative periods of the two wave forms, the sinusoid *a* and the saw-tooth *b*. For example, if the rise time of the saw-tooth is 1 millisecond and the period of the sinusoid is 10 microseconds, the electron beam will complete 100 revolutions as it moves radially from the center to the outer edge of the screen.

The circuit just described, although practical from the point of view of circuitry, has a prime disadvantage, which is the result of the nonconstant linear velocity of the scanning beam. The same sort of problem exists in the making of phonograph records. Since the angular speed (or speed of rotation) remains constant, the linear speed increases as the spot moves away from the center of the screen. On the cathode-ray tube this means that in the regions near the tube center where the linear velocity is low, the fluorescent screen is excited for a longer interval than are the outer portions of the screen where the electron beam is moving faster. This results in a spurious brightness modulation of the screen, which shows up as maximum brightness in the center and tapers off linearly to the edges. Compensation of the center brightness may be accomplished by applying a saw-tooth voltage to the control grid of the cathode-ray tube, which gradually raises the grid voltage as the scanning beam moves outward on the screen. Compensation of this type is difficult to accomplish, however, because of difficulties in properly combining the correcting

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voltage and the incoming picture signal voltage, which also must be applied to the control grid of the CRT.

This disadvantage alone is sufficient to rule out the circular picture and spiral scan for most practical purposes. Some further objection has been raised that the circular shape is not pleasing on aesthetic grounds. Probably the greatest single factor which caused elimination of a circular shape is that the cinema industry has standardized on a horizontal rectangle. Thus any television system which has hopes of using motion pictures as a source of program material is forced to eliminate the circular shape on the grounds that approximately 40 per cent of the picture information would be eliminated.

Two other picture shapes remain for discussion—the square and the rectangle. If a rectangle is inscribed in a circle it may be shown quite easily that its area will be maximum if it is a square; hence, of the two shapes the square gives better utilization of the circular tube face. Furthermore, scanning problems are minimized in a square picture and the simple horizontal linear scan shown in Fig. 2–1*a* may be used. Although this form of picture may be satisfactory for certain industrial or military uses, once again if moving pictures are to be used as program material, it must be ruled out because of loss of program material. It is of interest to note, however, that in several systems, designed specifically for naval and military use, the square picture shape has been rejected for the more common shape of the telecasting standards to be described.

The square may also be excluded on aesthetic grounds for, as Van Dyck[2] has pointed out, a rectangle of width-to-height ratio equal to unity is not "powerful" or "pleasing." Whereas this last reason for excluding the square is open to criticism on subjective grounds, at least the demands on a commercial telecasting system to transmit moving pictures makes the decision final for that type of service.

The remaining picture shape to be discussed is the rectangle, and although there are an infinite number of possible width and height combinations, it seems reasonable to choose those of the motion picture industry. Considerable argument has been put forth for this choice for commercial telecasting,[3] but the fact still remains that

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[2] A. Van Dyck, "Dynamic Symmetry in Radio Design," *Proc. IRE*, **20** (9), 1481 (September 1932).

[3] D. G. Fink, Ed., *Television Standards and Practice*. New York: McGraw-Hill Book Company, Inc., 1943.

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agreement with the cinema industry is advantageous to a new industry which must rely to a large degree on the relatively inexpensive and good-quality program material available on film.

It shall be assumed, then, in the rest of this book that the horizontal rectangle of width-to-height, or "aspect," ratio 4 to 3 is the standard of picture shape which gives a pleasing picture and is capable of handling all normal programming requirements.

2–2. An Estimate of the System Bandwidth

In order to discuss intelligently certain other standards we shall digress at this point to develop an approximate equation for the bandwidth required to transmit a television signal. It must be stressed that the following derivation is approximate and is based on rather crude assumptions. Its use is justified, however, because it does show exactly how bandwidth is related to the number of scanning lines and the rate at which the pictures are transmitted.

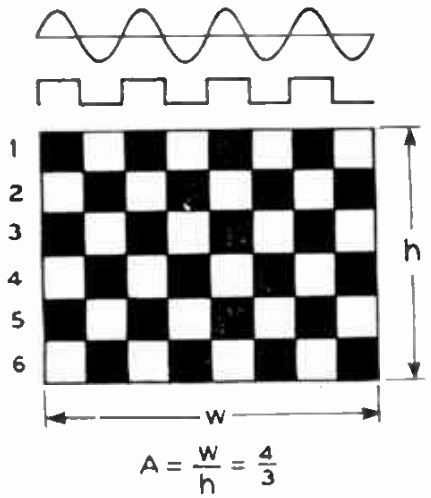

Fig. 2–4. The checkerboard pattern.

In Fig. 2–4 is shown a checkerboard pattern composed of alternate squares of black and white. Assume that this pattern is scanned by an aperture which is infinitesimally narrow but of the same height as the individual squares in the checkerboard. Assume further for the moment that the aperture is in perfect vertical alignment with the rows of squares, moves with constant velocity from left to right on row 1, returns in zero time from right to left, and then continues the scan on row 2 and so on. Under these conditions, the generated signal would be a square wave.

Now let N_v = number of elements along a vertical line,
N_h = number of elements along a horizontal line, and
f_p = frame frequency or number pictures scanned per second.

Then the number of cycles of square wave generated per picture is

$$\tfrac{1}{2}N_vN_h$$

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If it be further assumed that this square wave may be represented by its fundamental component, the frequency f_v of this component becomes

$$f_v = \tfrac{1}{2}N_v N_h f_p \tag{2-1}$$

and since $N_h = AN_v$ for the checkerboard, A being the aspect ratio,

$$f_v = \tfrac{1}{2}AN_v^2 f_p \tag{2-2}$$

Under the assumed condition that the aperture height is the same as that of the squares in the pattern, N_v is equal to n, the total number of lines in the scanning pattern, and we may rewrite (2-2)

$$f_v = \tfrac{1}{2}An^2 f_p \tag{2-3}$$

Now it will be realized that eq. (2-3) has been derived under an ideal condition because we assumed the scanning aperture to be in perfect vertical alignment with the rows of squares in the checkerboard pattern. Under this condition the reproduced image would be identical to the original image as shown at a' in Fig. 2-5; in general however,

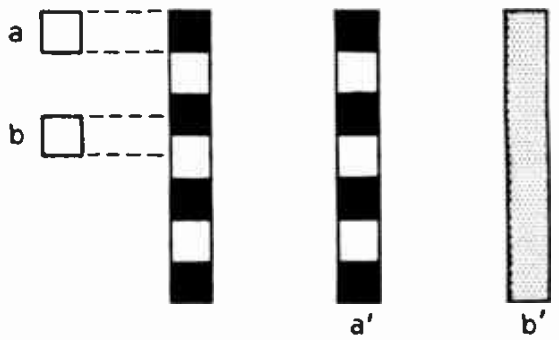

Fig. 2-5. Effect of aperture alignment on reproduced detail.

this ideal alignment will not occur and detail will be lost in the image because of it. For example, let us assume that the aperture is so much out of alignment that it just straddles two adjacent horizontal rows in the checkerboard, as shown at b in the figure. Then, since the aperture responds to the average brightness of the area which it covers, it will interpret the entire checkerboard as 50 per cent gray, and no detail would be reproduced as illustrated at b'. Between these two extremes of perfect and zero reproduction of detail lie any number of possibilities. It is evident, then, that eq. (2-3) obtains only in the ideal case. It has been customary, therefore, to introduce an empirical factor K, the utilization coefficient, into the equation to allow for

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the inevitable misalignment between the aperture and scanned material. For the general case, then, the expression for the maximum video frequency should be rewritten

$$f_v = \tfrac{1}{2}K_1 n^2 f_p \tag{2–4}$$

Kell, Bedford, and Trainer[4] have recommended a value of 0.64 for the coefficient on the basis of resolution tests and this value has been widely accepted throughout the industry.

It must be realized that the checkerboard described above, where square and aperture heights are equal, represents the top limit of the system. Thus f_v in (2–4) is the maximum video frequency. For larger elements in the picture, f_v will be lower, and in the limit the average brightness of the entire field of view shows up as a d-c component. Thus the bandwidth of the system extends from zero frequency to f_v. Hence (2–4) is also an approximate relationship for the bandwidth of the system.

It must be admitted that eq. (2–4) is an approximation only. We shall see in Chapter 10 that the checkerboard pattern is a poor choice to test the resolution of a television system. Its use here is justified on the grounds that it is a pattern which has equal vertical and horizontal resolution: the ratio of elements on a horizontal line to those on a vertical line is identical to the aspect ratio. Furthermore, we assumed an infinitesimally narrow scanning aperture, a condition which cannot be fulfilled in practice. Nevertheless, eq. (2–4) is of value because it shows how the bandwidth required for transmitting a television signal is related to the number of scanning lines and to the frame frequency.

With eq. (2–4) the digression is complete: an equation has been derived giving an approximate expression for the bandwidth of a video system which is proportional to n^2 and to f_p, the picture repetition frequency. Some feeling for the order of magnitude of the quantities involved in television practice may be had by direct substitution into eq. (2–4). Thus a 500-line system sending 30 pictures per second requires an approximate video bandwidth of

$$f_v = \frac{0.64}{2}\left(\frac{4}{3}\right)(500)^2(30) = 3.2 \text{ megacycles.} \tag{2–5}$$

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[4] R. D. Kell, A. V. Bedford, and M. A. Trainer, "An Experimental Television System," *Proc. IRE*, **22**, 11, 1247 (November 1934).

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Notice also that a 4:1 reduction in bandwidth may be obtained by using only 250 scanning lines, but the resolution or detail in either the horizontal or vertical direction would be reduced by two.

2–3. Speed and Direction of Scan

In choosing the horizontal rectangle as the standard picture shape it is assumed that the picture will be scanned in straight parallel lines. Four additional requirements on the scan are of concern here. First, regardless of its direction the scan must proceed with a constant linear velocity. This is necessary if the resolution is to remain constant over the entire picture area. Stated in other terms, constant linear velocity of scan permits equal fineness of detail in all parts of the picture. That this is a desirable condition may be seen from the following consideration: It is well known that the light-sensitive area of the eye, the retina, is made up of bundles of rods and cones. Since these are of small, yet finite, size the ability of the eye to resolve or separate two dots under view is limited. Experiments tend to indicate that on the average the eye can distinguish the two dots as being separate if they subtend an arc of one minute[5] or more. In the reproduced television picture, the information is presented in the form of small areas, each of constant brightness. Hence the viewer has a tendency to adjust his viewing distance until adjacent areas blend into a continuous picture. This distance will depend, of course, upon the element separation in the picture or upon its resolution. Thus if different areas in the picture have different resolutions, the viewer tends to increase his viewing distance to render satisfactory the poorer parts of the image. This results in loss of detail in the higher quality regions and so the "best" parts of the picture are wasted in a sense. This sort of reasoning justifies the demand for constant linear velocity of scan.

Consider the second additional requirement on linear scan, namely, that it shall be unidirectional. More specifically it is meant here that picture data shall be presented only as the aperture moves in one direction and not in the reverse direction also. The reason for this is primarily one of circuitry. For example, if a device employing electrostatic deflection of the electron beam is used, a more complex deflection voltage is required for a bidirectional scan. Figure 2–6

[5] E. W. Engstrom, "A Study of Television Image Characteristics," *Proc. IRE*, **21**, 12, 1631 (December 1933).

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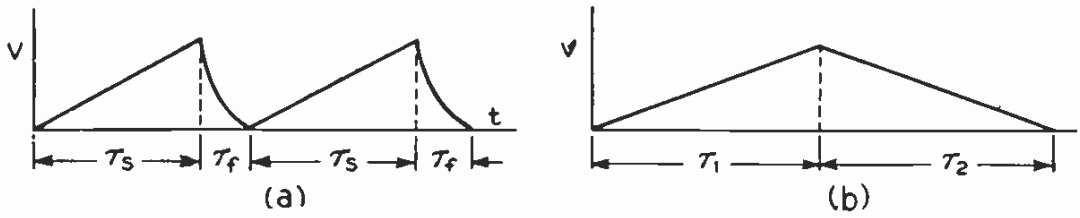

Fig. 2–6. (a) Deflection voltage for unidirectional scan. (b) Deflection voltage for bidirectional scan.

shows the deflection voltages required for unidirectional and bidirectional types of scan. At *a* the former is shown. Picture data is presented only during the scan intervals τ_s, τ_f, the flyback interval, being used to return the aperture to its starting position. During τ_s the voltage must build up linearly with time to provide constant resolution. During τ_f, on the other hand, the voltage may follow *any* mathematical function of time just so long as it reaches its initial value at the end of τ_f. At *b* the bidirectional scan requirement is shown. During both τ_1 and τ_2 the deflection voltage must change linearly with time, once increasing and then decreasing, i.e., the deflection voltage must be an even function of time. It may be seen that the requirements in the former case are less severe. Furthermore considerable difficulty is encountered in building circuits to meet the requirements of linearity during τ_2 in curve *b*. Generation of the voltage shown at *a* may be accomplished by the use of a series *R* and *C* circuit and is discussed in Chapter 4. A further disadvantage is present with the bidirectional scan in that an overlapping of adjacent lines, which have finite width, occurs at the edges of the scanned pattern.

The third consideration relative to the linear scan is its direction. Clarification is required here because actually two directions of scan are involved. A moment's reflection will show that if a moving aperture is to cover the entire area of the rectangular image, it must move in two directions. The assumption has been made in the discussion thus far that the aperture moves with constant velocity along a "line," returns to the picture edge corresponding to its initial position and scans another "line" parallel to the first, separated from it by the dimension of the aperture normal to the "line." The question here, then, is shall these scanning lines be horizontal or vertical as shown in Fig. 2–7*a* and *b*, respectively? Actually the horizontal direction has been chosen as standard, first, because it conforms to the direction of writing English, and, second, because there is a feeling

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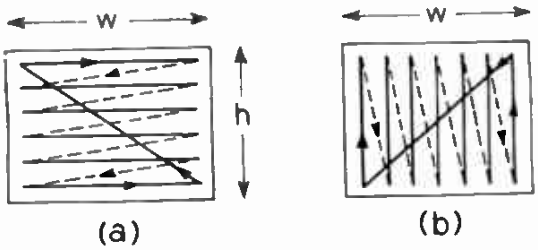

Fig. 2–7. Types of scan. (a) Horizontal. (b) Vertical.

in some quarters that the horizontal scan is better able to reproduce motion, which is predominantly horizontal rather than vertical, in typical televised scenes.

The fourth consideration pertaining to the linear scan is its sense, i.e., shall the aperture during the scan interval move from left to right or vice versa. No technical advantage is at stake in the selection to be made here, and again the "natural" choice seems to be to conform to the direction of writing English. Hence the standardized scan senses are from left to right and from top to bottom of an upright reproduction of the image televised.[6] The last clause may seem to be superfluous but it is necessary because in the pickup end of the system an optical image of the scene is thrown on a photosensitive surface by a lens. This image is inverted relative to the physical world and, hence, must be scanned from right to left and from bottom to top in order that scanning conform to the standard.

Two other questions inevitably arise relative to scan at this point. The first is: What shall be the flyback ratio defined by

$$p = \text{flyback ratio} = \frac{\tau_f}{\tau_s} = \frac{\text{retrace or flyback time}}{\text{trace or scan time}} \qquad (2\text{–}6)$$

where τ_f and τ_s are the intervals shown in Fig. 2–6*a*? The second is: What shall be the number of lines, which in the final analysis determines the resolution of the entire system? Both of these questions more properly relate to the requirements of the particular television system under consideration and as such are treated in another section. For the moment we may at least say that p should be as small as practicable in order that a minimum of time be lost from the scanning process.

[6] It is interesting to note that Fink reporting on the deliberations of the National Television Systems Committee, which set up the proposed standards for commercial television service for the Federal Communications Commission, states that the sense of scan, in contrast to several other standards, was adopted unanimously. D. G. Fink, *op. cit.*, p. 195.

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These scanning standards may be summarized as follows: The active picture area shall be scanned in parallel lines, horizontal (or nearly so) and from left to right. The sequence of lines will be from top to bottom of an upright picture image. The scan in both horizontal and vertical directions shall be at a constant speed.

2–4. The Frame Frequency or Picture Repetition Rate[7,8]

Thus far in the discussion it has been shown that the picture information of the television picture is built up element by element until the entire field of view has been supplied with brightness information. Such a single scan of the entire picture area may be called a "picture" or a "frame." The latter notation, which is more commonly used, is derived from moving picture terminology, wherein a single complete picture in the series of pictures on the film is termed a frame. It has been shown further that these pictures or frames are then presented in sequence at a rate sufficiently high, such that the resulting picture satisfies the requirement for fusion of all the elements into a smooth picture, for reconstituting motion in the original scene, and for unnoticeable flicker. It remains at this point to investigate the factors that control these considerations.

At the outset it must be stressed that the disagreement between standards for industrial or military applications on the one hand, and for commercial telecasting on the other may be considerable. In setting up the requirements for the commercial system[9] the criterion for "satisfactory operation" is the performance of the 16-millimeter sound moving picture system. In the former applications performance below this par may be tolerated and, in fact, may be mandatory in order that other requirements such as system simplicity, lightweight components, and minimum cost (where equipment life may be relatively short)[10] may be met.

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[7] E. W. Engstrom, *op. cit.*

[8] E. W. Engstrom, "A Study of Television Image Characteristics," Part II. *Proc. IRE*, **23**, 295 (April 1935).

[9] It should be mentioned that the remarks of this section apply to the standard commercial black-and-white television system. Developments have been made in color television systems and in the so-called "dot-interlace" system of transmission which permit frame frequencies considerably lower than 24 per second to be used without adverse effect on the reproduced picture.

[10] In the "Roc Bird" a miniature pickup and transmitting system is mounted in a bomb. The entire airborne system weighs but 50 pounds and is blown up at the end of the flight. *See* R. D. Kell, and G. C. Sziklai, "Miniature Airborne Television Equipment," *R.C.A. Rev.*, VIII, 3 (September 1946).

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Thus, since the 16-mm movie uses 24 frames per second as the frame, or picture repetition frequency, f_p, this value sets the lower limit for the commercial telecasting system. Hence, $f_p \geq 24$ frames per second and it need only be determined what the actual value shall be. For the more general case, however, some investigation must be made as to the factors which place a lower limit on f_p. From the viewpoint of reproduction of motion, it has been determined that the eye sees no discontinuity of motion if the frame frequency exceeds 16 pictures per second. This low value of f_p is generally unsatisfactory because of the accompanying flicker. Hence we now consider flicker which is the first of these factors to be discussed.

If a beam of light of constant intensity be interrupted at a variable rate, it may be shown experimentally that above a certain minimum interruption frequency the eye responds as if it were receiving the light stimulus continuously. Under these conditions the separate stimuli arrive at a rate which is high enough for the eye to integrate the intensity over a complete cycle, and the effect is just as if a source of constant intensity were shining continuously. At frequencies below this critical value the eye is unable to so integrate the information; it sees the instantaneous variations. In this case flicker is said to be present and the frequency at which crossover between the two effects occurs is known as the critical flicker frequency.

If, now, the same experiment be performed at different levels of source intensity, it is found that the critical flicker frequency varies with the logarithm of the illumination intensity. This is a statement of the Ferry-Porter law and is illustrated in Fig. 2–8. Data for these curves were taken by Engstrom by having several observers view the image of a light source focused on a screen, the light beam being chopped by the rotating disk shown in the diagram.

If these results are to be related to television the immediate question is this: To what angle of disk opening, b, does the television system correspond? In the absence of a complete set of standards this question cannot be answered rigorously at this time. Some order-of-magnitude conclusions may be drawn, however. Consideration of the scanning pattern previously proposed shows that after a complete frame has been scanned, the scanning aperture must return to its starting point at the top left-hand corner of the picture. A finite time is required to accomplish this retrace, or flyback, in the vertical direction. From considerations that will become apparent

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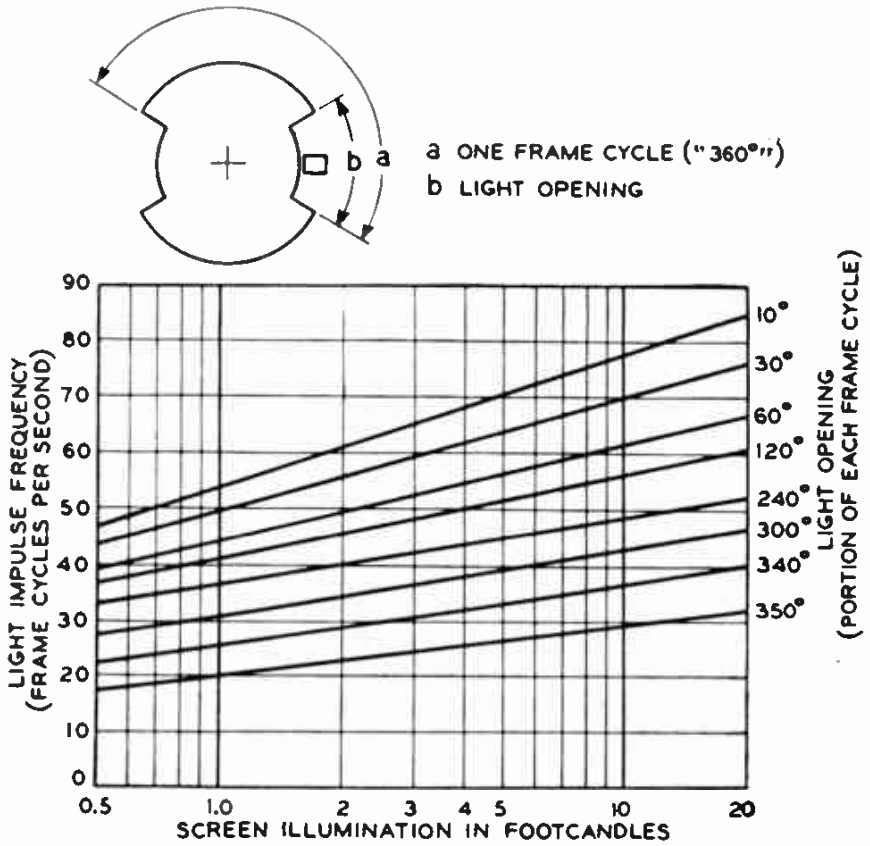

Fig. 2–8. Critical flicker frequency measured with a slotted disk. (Courtesy of *Proc. IRE.*)

later in our work, this vertical flyback ratio, p_v, which is defined in (2–6) is generally of the order

$$p_v = 0.05$$

That is to say that the ratio of retrace to trace time is 0.05. Since the electron beam is "blanked out" during retrace to prevent contamination of the picture, this means that the eye sees light for approximately 95 per cent of the frame interval which corresponds to a disk opening of approximately 340° in Fig. 2–8. It would appear, then, that a 340° opening curve could be used for determining the critical flicker frequency. As a practical matter this guess does not correspond to the facts because the type of flicker generated in Engstrom's test does not correspond to that present in the television system. Despite this fact, which will be expanded presently, the curves of Fig. 2–8 do show, first, that the Ferry-Porter law obtains and, second, that if the screen viewed during the test were located in an ambient light level other than zero, the same results

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would hold true, provided the abscissas were interpreted as apparent illumination, i.e., the difference between the illumination of the test screen and the ambient level of illumination.

In the preceding paragraph it was stated that the flicker present in a television image and in the test previously described are different. This is easy to see when the two systems are compared even in the most elementary respects. First, in the test for almost the entire slot width b, the whole screen is illuminated uniformly. On a CRT screen, on the other hand, only a few elements are illuminated at a time as the spot traces out its pattern of straight, parallel lines. Note the difference then: Entire screen illumination during the unblanked scan time as compared to partial screen illumination—with the illuminated area moving so as to cover the entire field of view in the unblanked scan time.

As might be expected, in the latter case where the conditions are more severe, a higher value of critical flicker frequency obtains. Thus a curve corresponding to a light opening of considerably less than 340° in Fig. 2–8 more closely approximates the actual conditions that exist in a television system.

An additional factor aids the retina in integrating the image over the scan period and that is that the illumination of an excited phosphor on a CRT tends to persist; it decays exponentially after the excitation is removed rather than dropping to zero instantaneously. Realizing this, Engstrom has conducted additional tests to measure the flicker threshold on an actual cathode-ray tube. The results of this test are given in Fig. 2–9, which shows critical flicker frequency vs.

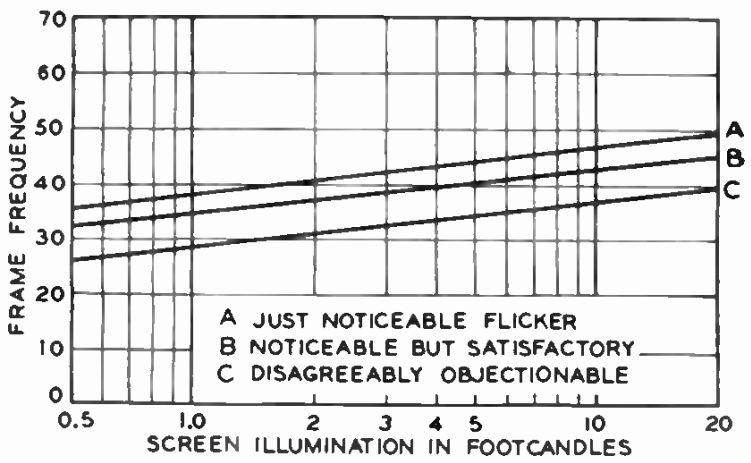

Fig. 2–9. Critical flicker frequency for a cathode-ray tube. (Courtesy of *Proc. IRE.*)

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apparent illumination on the kinescope. The persistence characteristic of the cathode-ray tube used for the test is shown in Fig. 2–10.

In applying Fig. 2–9 to any television system, it must be realized that any curve is not absolute; it may be displaced vertically, depending on the persistence characteristic of the particular fluorescent material used on the viewing screen. The curves of Fig. 2–9 and 2–10 are typical, however, for the P4 screens commonly used for television service.

We are in a position now to decide on the value of flicker frequency for the television system. The choice is inevitably dependent upon the level of apparent illumination required. In the lack of a better criterion we may turn to the 16-millimeter sound moving picture system for a guide. Goldmark[11] has presented the following data:

Levels of Illumination for 16-millimeter Movies

Condition	*Apparent illumination on 3-ft wide screen*
No film in gate	10 foot-candles
Clear film in gate	8 foot-candles
High lights in color film	4 foot-candles

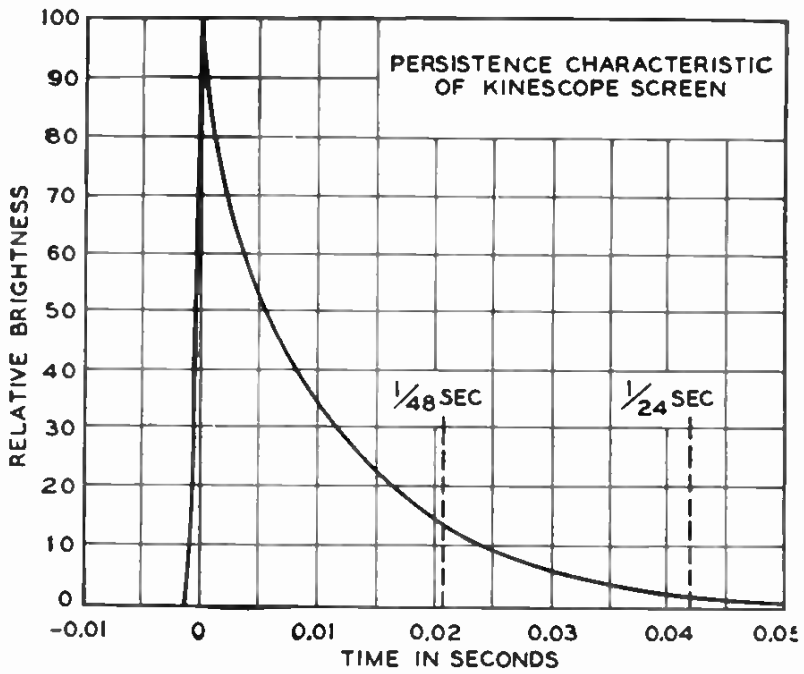

Fig. 2–10. Persistence characteristic of the cathode-ray tube screen used in obtaining the data for Fig. 2–9. (Courtesy of *Proc. IRE.*)

[11] P. C. Goldmark, First Lecture in the Series Modern Television, *New York Section IRE* (Fall 1948).

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Using these figures as representative, reference to Fig. 2–9 shows that a flicker frequency of some 45 "flicks" per second are needed. Yet the 16-millimeter movie system displays only 24 frames per second. The discrepancy between these two figures of a factor of about 2 to 1 may be explained by a simple device that is used in the movie projectors.

In the first place, movie flicker is of the type given by the slotted-disk test described previously. Thus a lower value than that for the television system is permissible, but at any rate, it will be greater than the 24 frames per second displayed by the 16-millimeter sound movie system. As we have seen, this figure is perfectly satisfactory for reconstituting motion in the scene and presents enough footage of film for satisfactory sound reproduction. Thus raising the frame frequency to meet flicker requirements would result in the use of greater lengths of film with little improvement of the picture (except, of course, with regard to flicker). To obviate the need for this waste of film, a rotating slotted disk, not unlike that of Fig. 2–8 is incorporated in the projection system. The bislotted disk revolves once in the time that each frame is in the film gate. Thus, light is projected twice onto the screen through each film frame, and the 24 frames per second on the film appear as 48 "flicks" per second on the screen. In this manner the flicker frequency for the cinema is raised well above the threshold value.

But the objection might well be raised that all this talk is about a moving picture system; how does it tie in with television? Following this line of thought, it seems that it is only necessary to refer to Fig. 2–9 to determine the critical flicker frequency corresponding to the apparent illumination required by the given application, and to choose the next higher, convenient value of frequency as the frame frequency for the television system. The objection to this procedure is furnished by reference to equation (2–4) which shows that the bandwidth of the video system is directly proportional to f_p, the frame frequency. It is in the interest of bandwidth economy, then, to choose a frame frequency as low as possible. A compromise is indicated: f_p must be chosen to effect a balance between video bandwidth on the one hand, and unnoticeable flicker on the other. The compromise depends upon the requirements of the particular television system being designed.

At this point the 2 to 1 flicker-frame relationship described for the

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moving picture projector seems intriguing. If a similar device could be adapted to the television system, a 2 to 1 saving in video bandwidth could be effected with no degradation of the flicker characteristic. Because of the sequential manner in which the picture information is presented on the CRT it is impossible to incorporate a rotating slotted disk as described above. It remains, then, to see if some alternate mechanism can be proposed which will achieve the same result.

In 1931 U. A. Sanabria[12] proposed a system of interlaced scanning that effectively gives two vertical flyback and blanking periods during the presentation of a single frame which accomplishes the same overall result. Figure 2–11 shows a number of lines covering the picture

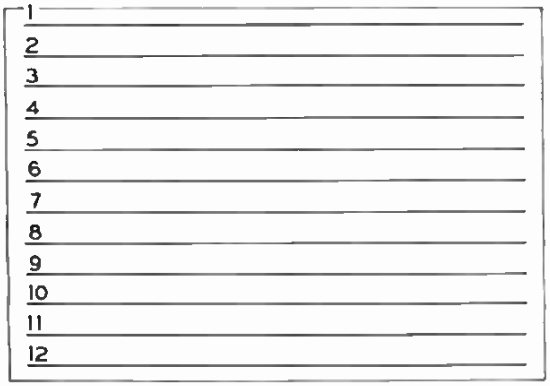

Fig. 2–11. Position of an arbitrary number of scanning lines. Progressive scan results if the lines are scanned in order from top to bottom. The sequence 1, 3, 5, 7, 9, 11, 2, 4, 6, 8, 10, 12 is used in interlaced scanning.

area. These lines are scanned in a "progressive" scan of the type already described, in the order of the numbers shown, i.e., 1, 2, 3, · · ·, from top to bottom. At the end of line 12, the spot retraces vertically during the vertical blanking interval back to its starting point on line 1. As the name implies, in the interlaced system of scanning, two sets of lines, which interlace each other, are scanned alternately. Thus, for example, in Fig. 2–11 the scanning sequence would be 1, 3, 5, 7, 9, 11 retrace to the beginning of line 2 with the beam blanked out, then lines 2, 4, 6, 8, 10, 12 and retrace with the beam blanked out to the beginning of line 1.

If this interlaced scanning sequence is carried out, each picture is scanned in two interlaced halves composed of alternate lines with two

[12] U. A. Sanabria, U. S. Patent #1805848, March 1931.

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blanking intervals, and the desired flicker-to-frame frequency ratio of 2 to 1 is accomplished. Each half-picture which is composed of one set of alternate lines is termed a "field" and the field frequency, f_f, is seen to be twice the frame frequency, where a 2 to 1 interlace of 2 fields to a frame is used.

Use of this interlaced scanning pattern imposes more severe restrictions on the scanning systems and, as will be seen in Chapter 3, demands that the sum of the active scanning lines plus the inactive lines lost during the vertical retrace intervals be an odd number.

A critical examination of the flicker present in this interlaced scanning system shows that actually two flicker effects are present. The first or "over-all effect" is the result of each line flickering at the rate of once per frame. The second is the "interline effect," caused by adjacent lines flickering in a time relationship differing by one field period. These two effects were also the subject of a series of tests performed by Engstrom. Again resorting to tests employing a rotating disk slotted in a different manner (Fig. 2–12), he was able to

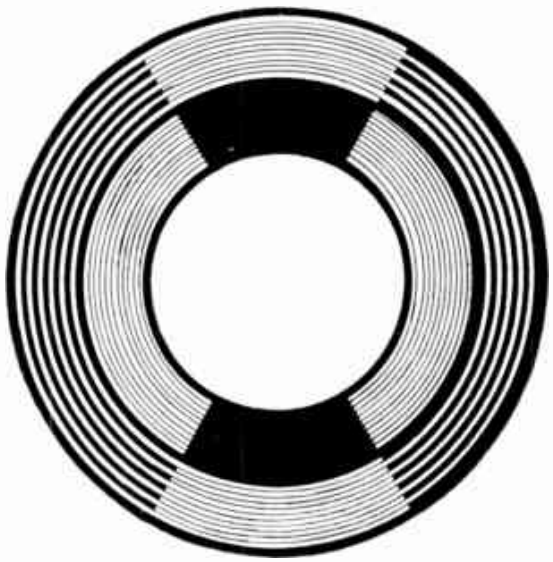

Fig. 2–12. Special disk used by Engstrom for interlaced scanning flicker tests. (Courtesy of *Proc. IRE.*)

draw some general conclusions. The interlaced scan pattern does minimize flicker, but the viewing distance must be increased over that required with progressive scan in order to minimize the interline flicker. Once again, the hangover or persistence characteristic of the CRT phosphor aids in creating the illusion of a fused picture and the interlaced system has been adopted as the commercial standard in

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the United States of America. It must be stressed, however, that it *need* not be used; the interlaced scan pattern may be used where the 2 to 1 saving in bandwidth for a given flicker and illumination requirement is desirable at the expense of a more complex system.[13]

Summarizing, it appears that the choice of frame frequency is contingent upon a number of factors, all peculiar to the particular television system under consideration; screen illumination, flicker requirements, bandwidth, and permissible degree of system complexity. We digress on additional requirements peculiar to commercial telecasting.

It has been pointed out repeatedly that agreement between cinema and commercial television standards wherever possible is highly desirable from the programming viewpoint. It seems reasonable, then, to standardize the frame frequency at 24 frames per second which is common to both 16–mm and 35-millimeter moving picture systems. This with a 2 to 1 interlaced scan would place the flicker frequency at 48 flicks per second. Reference to Fig. 2–9 shows that this choice would permit operation at levels of apparent illumination up to some 10 foot-candles. Unfortunately other factors must be taken into consideration. Foremost among these is the effect of power supply ripple frequency on the scanning pattern.[14]

Probably one of the most objectionable defects in a televised image is unsteadiness. On this basis, we may investigate some of the undesirable effects caused by spurious modulation of the scanning pattern produced by power supply ripple voltages. Since commercial standards are based on an interlaced scanning geometry, let us determine what effect, if any, these ripple voltages will have on an electrostatic deflection system operating at 24 frames, 48 fields per second. As a specific example, we shall consider what happens to the horizontal scanning lines.

It must be realized at the outset that if ripple components appear on the horizontal deflecting plates of the cathode-ray tube, spurious sidewise displacements of the scanning lines will occur. Assume for

[13] The military systems previously mentioned illustrate this point. In the Ring system where the pickup equipment is carried in a bomber, a 2 to 1 interlace is used. The Block systems which enjoy a comparatively short life in a guided missile use the simpler progressive scan. *See* V. K. Zworykin, "Flying Torpedo with an Electric Eye," *R.C.A. Rev.*, **VII**, 3 (September 1946).

[14] R. D. Kell, A. V. Bedford, and M. A. Trainer, "Scanning Sequence and Repetition Rate of Television Images," *Proc. IRE*, **24** (4), 559 (April 1936).

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illustration that a half-wave rectifier operating from a 60-cycle line is the voltage source for the circuit. Then the fundamental ripple component will modulate the lateral positions of the scanning lines at a frequency of 60 cycles per second. Since in the 24/48 frame-field system proposed each field has a duration V of 1/48 second, the number of spurious ripple cycles per field will be

$$\text{No. of ripples/field} = \frac{60}{48} = 1.25 \text{ cycles/field} \qquad (2\text{–}7)$$

The result of this spurious deflection of the scan pattern is shown in Fig. 2–13, where the lines of field 1′ are displaced vertically so that

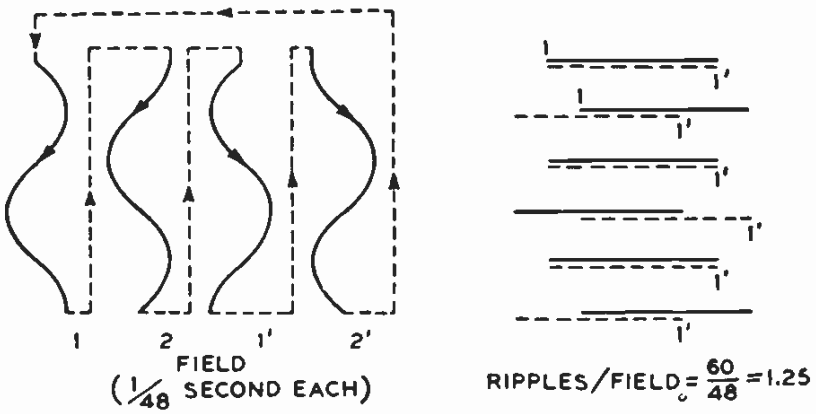

Fig. 2–13. Spurious line deflection due to 60-cycle ripple in a 24/48 interlaced scanning system. Any line moves horizontally between alternate fields. (After Kell, Bedford, and Trainer.)

their positions may be seen. Since the field and ripple frequencies are not integrally related, the envelope of the line positions for field 1 and 1′ (and for fields 2 and 2′ for that matter) are not the same. This means that a given line in alternate fields will occupy different positions causing an objectionable unsteadiness in the final image. Just how objectionable this effect will be depends, of course, upon the magnitude of the spurious deflection. A simple calculation will show that if the envelope amplitude is 25 per cent of the interline spacing, the maximum change of position of a single line is approximately 100 mils on a 10-in. CRT. This value may cause considerable degradation of the picture. A quick estimate of the situation shows that remedial measures may follow two avenues. First, the ripple voltage may be reduced at the expense of adding more filtering to the

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power supply, or second, the frame and field frequencies may be increased so that they are related integrally to the power line frequency. An increase rather than decrease in these frequencies is necessary in order that flicker requirements may be met, but the price to be paid is an increase in video bandwidth. Other factors tend to favor a choice of the latter alternative and in telecasting the 30 frame-60 field per second values are chosen as standards.

If ripple voltage is present in the display equipment, it will probably also appear on the control grid of the kinescope. Its effect here will be to produce dark horizontal bars across the face of the televised picture. Furthermore in the 24/48 frequency system, these bars will move downwards across the face of the picture. A change to a 30 frame-60 field system will not eliminate the bars but at least they will remain stationary.

Since line position modulation and the bar pattern described above may be minimized by additional filtering and shielding, let us next consider an effect completely independent of ripple within the television equipment. The tendency over the post-war period has been to a larger number of remote pickups at points other than the television studio. At these remote locations direct current is virtually never encountered. Since all light sources operating from a-c sources have a stroboscopic effect, hum signals are picked up by the television camera tube. If of sufficient amplitude, these may produce dark bar modulation which moves vertically on the screen when the light source and field frequencies differ. With the 30/60 frequency standards the dark bars remain stationary.

It must be realized that only a few of these ripple effects have been mentioned. A more complete analysis such as that presented by Kell, Bedford, and Trainer must take additional account of spurious *vertical* deflection of the scan lines or "pairing," spurious effects as a result of higher ripple frequencies, and the like. All these considerations point to the adoption of a 30 frame-60 field system as opposed to the 24/48 system of the cinema industry. The disagreement between these two systems is unfortunate for it requires a conversion of the 24 movies frames per second into 30 frames per second for the television system when film is televised. This conversion may not be accomplished by simply increasing the film speed in the ratio of 5 to 4, for motion would be speeded up with the humorous effect

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of films of the 1920's run in modern projectors.[15] Since the sound track is on the same film as are the pictures, the increased speed would cause improper sound reproduction. How the conversion of film to television standards is accomplished without speed-up of the film is covered in Chapter 17.

Care should be taken to realize that adoption of the 30 frames and 60 fields per second does not eliminate the various ripple effects discussed, but it does minimize them. Because of the 1 to 1 relationship between supply and field frequencies, the envelope of the spurious line deflection has only 1 cycle per frame and the result is shown in Fig. 2–14. Notice that here the field-to-field motion of any given

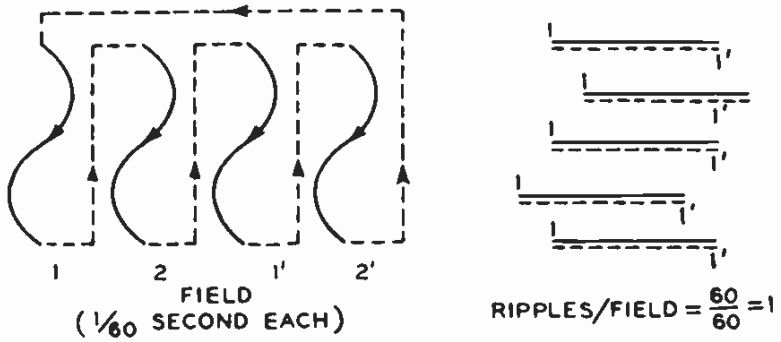

Fig. 2–14. Spurious line deflection due to 60-cycle ripple in a 30/60 interlaced scanning system. Field-to-field motion of the lines is eliminated. (After Kell, Bedford, and Trainer.)

line in the scan pattern is eliminated. Furthermore, the maximum peak-to-peak motion of a line is replaced by a fixed peak displacement from the normal of about 50 mils for the same conditions assumed in the previous example.

Whereas the discussion above was carried out for the commercial system which employs interlaced scan, it must be emphasized that a similar treatment will show that an integral relationship between power line and frame frequencies in a progressive scan results in the same sort of improvement.

In summary a balance sheet may be prepared comparing the two systems of standards.

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[15] The old silent films were taken at 16 frames per second. The playback speed was from 16 to 30 frames per second depending upon the whim of the projectionist. The advent of the sound track made rigid adherence to a constant speed of 24 frames per second (90 feet per minute) mandatory.

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	24/48 system	*30/60 system*
Power line frequency	60 cps	60 cps
Spurious line deflection	Yes	Yes
Spurious horizontal line motion	Yes	No
Spurious vertical deflection	Yes	Yes
Spurious vertical line motion	Yes	No
Black bar pattern	Yes	Yes
Motion of bar pattern	Yes	No
Flicker	Satisfactory	Satisfactory
Bandwidth	Δf	$\frac{5}{4}\Delta f$

In retrospect it is interesting to consider the verisimilitude of the assumption of a 60-cycle power line frequency which was made in the foregoing discussion. This is standard for most of the United States with two principal exceptions. Generation of power in the Niagara Falls section is at 25 cycles per second. St. Louis and certain parts of Metropolitan New York enjoy this distinction also, but in the latter region the service is being converted to 60 cycles per second, except for industrial loads. In large areas of California where the frequency is locked in with adjacent 60 cycle areas 50 cycles has been standard. In none of these regions would adoption of the 24/48 standards give improved service over the 30/60 system.

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CHAPTER 3

SCANNING METHODS

We have seen in the previous sections that the scanning process is basic in television, that picture transmission requires that some sort of sampling aperture be made to move across the entire picture area in some orderly, predetermined fashion. Furthermore, in setting up means of determining the picture standards we confined the discussion to receiving-end terms where a cathode-ray tube was assumed to be the display device. This led to the general notion that scanning involves the deflection of an electron beam. The immediate question, then, is whether or not both ends of the system scan by the same method, thus making the previous discussion of picture standards general. Now it must be realized that the present day all-electronic system evolved in more or less definite steps. Let us briefly review some of the major scanning methods that have been used for television transmission over a period of the last twenty years.

3–1. Mechanical Scanning

In 1884 P. Nipkow proposed a mechanical means of scanning an image which involved the use of a rotating disk. The development of this scanning device may be described on the following basis. If an area wh is to be scanned in its entirety by a single aperture, that aperture must be made to move in two directions. This bidirectional motion of a single aperture may be replaced, however, by motion in a single direction of an array of apertures which are displaced from each other in two dimensions. To make this more clear, consider Fig. 3–1. If the array of apertures, n_a in number, is moved downward at a constant velocity, the entire area wh will be scanned in a series of vertical lines. Certain restrictions on the dimensions of the scanning array must be made so that only one of the several apertures is on the picture area at any given instant. From the diagram it can be seen that the vertical inter-aperture distance must be equal to or greater than h, the picture height, and if adjacent lines are to touch each

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other, the width, a, of the aperture must be w/n_a, where w is the picture width and n_a is the number of identical apertures in the scanning array.

It is apparent that if the picture area is to be scanned continuously,

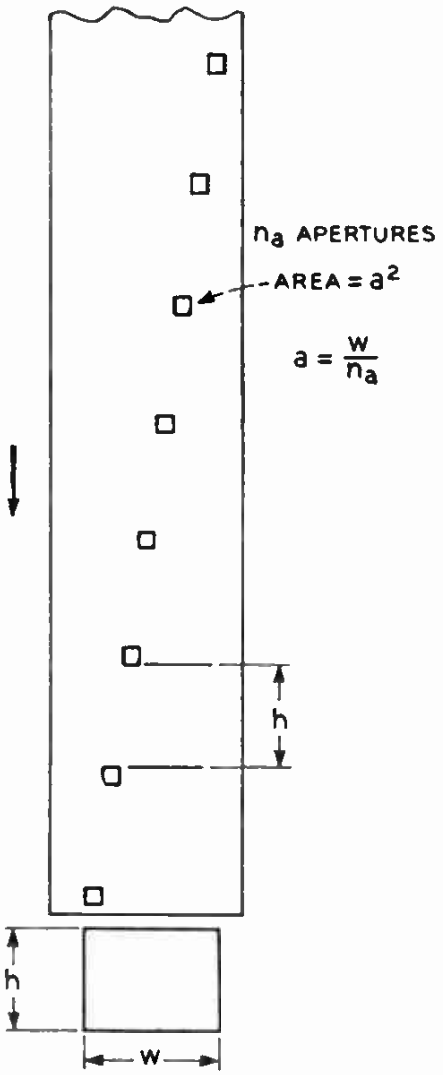

Fig. 3–1. A single aperture that moves in two directions may be replaced by an array of apertures that move in one direction.

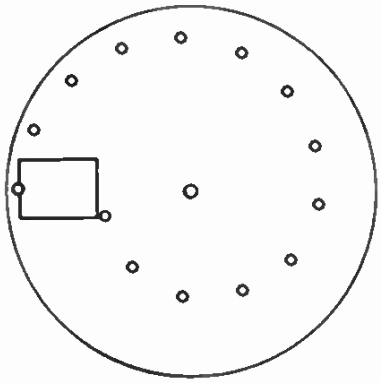

Fig. 3–2. The Nipkow disk.

an infinite number of such scanning arrays would be required. Clearly, a compromise is indicated. One such compromise is this: let the array of n_a apertures be closed back on itself to form a spiral and let the vertical motion of the array be replaced by a rotational one. This substitution results in the Nipkow disk, with n_a apertures arranged in a spiral, and this disk is to be rotated at a constant angular speed. Notice that the only change in scanning different from that of the original system is that the lines are sections of circles whose centers are located at the shaft.

Given the Nipkow disk as a scanner a simple mechanical television system may be set up. Let a phototube be placed behind the disk. Then, because of the scanning action of the pickup disk, the phototube "sees" only one element of the object at a time. The amplified output of the phototube is delivered by the link to a neon tube opera-

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ting in the region of abnormal glow, causing the total light intensity to be proportional to the object brightness. The brightness information is restored to its proper position in space by a second Nipkow disk operating in exact synchronism with the first. The simple circuit which is shown in Fig. 3–3 represents one of the earliest steps in the development of television systems.

The chief disadvantages of the double Nipkow disk apparatus are more or less self-evident and are listed below.

(1) Picture size is limited by the maximum allowable disk dimensions and the size limitations of the playback discharge tube. In the early stages of the art a 1-in. square image was typical.

(2) n_a, the number of lines, and hence the resolution, is limited by the scanning-disk size.

(3) The reproducing tube does not give off white light causing the gray scale to be replaced by shades of some monochrome.

(4) The system scanning speed is limited by mechanical considerations, e.g., by motor rotation.

(5) The efficiency of the optical systems is low. In illustration of this fifth point it can be seen that despite the high illumination of the object being televised, the instantaneous output of the phototube is proportional only to the illumination of the very small area framed by the aperture.

The next principal stage of development incorporated the "flying-spot" scan at the pickup end to increase the optical efficiency. It may be noted that in Fig. 3–3 the televised object is under constant

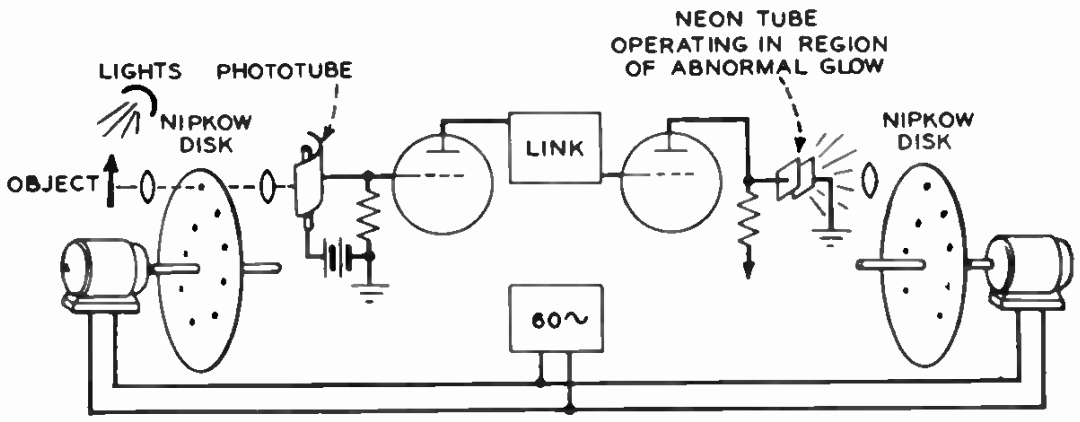

Fig. 3–3. A simple television system employing mechanical scanning.

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high-level illumination, and the phototube effectively scans across the area. In the flying-spot scanner, on the other hand, the televised object is in darkness and is viewed by a battery of phototubes. Illumination in the form of a moving light spot of high intensity is then caused to scan across the object by a scanning disk. As a result of concentrating all available light on a single picture element and using several, rather than a single, phototubes for pickup, a greater output is obtained than in the previously described system. Reference to Fig. 3–4 shows that the prime difference between the two systems lies in the placement of the scanning disk relative to the lighting source, the object, and the phototube. In the earlier system, the scanning disk lies between the illuminated object and the transducer. In the flying-spot scanner, the disk is between the light source and the object. In the interests of even greater optical ef-

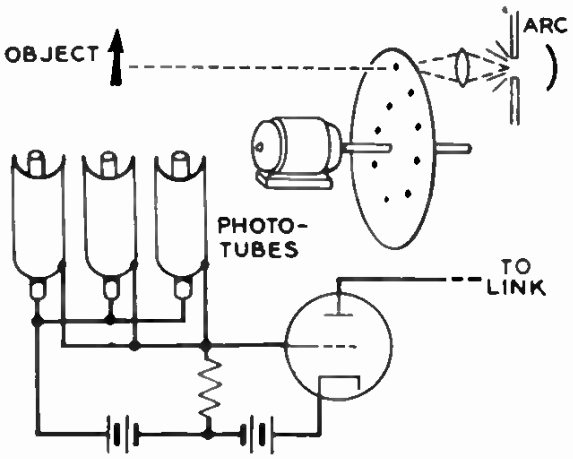

Fig. 3–4. Flying spot scanning.

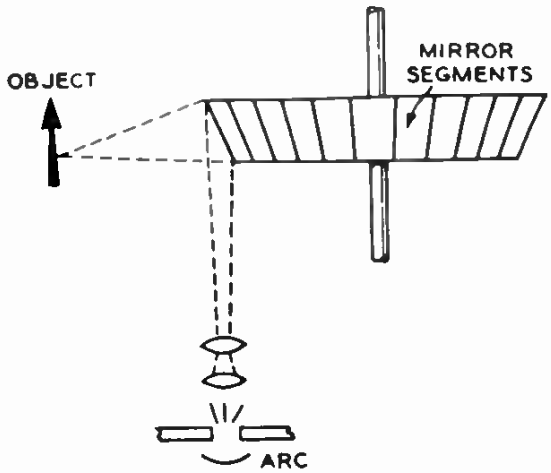

Fig. 3–5. Mirror scanner.

ficiency, the Nipkow disk was later replaced by a revolving drum with lenses over the individual apertures.

It must be realized that in this same period of development several other mechanical systems of scanning at both pickup and reproducing ends were developed. As an example, a rotating mirror scanner is shown in Fig. 3–5. Here the spot of light is made to scan the image by rotating a drum of tilted mirrors, each having a tilt which gives a scanning line at a height different from all the others. For our discussion little advantage is to be gained by reviewing the details of each system, for all agree in the essentials. It should be mentioned,

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however, that the Scophony[1,2,3] system, involving double rotating mirrors whose axes are normal, was used—though primarily in Europe—for reproducing the image. Its chief advantage lay in its ability to project relatively large images at the receiving end. The principal components of the Scophony apparatus are diagrammed in Fig. 14–35.

3–2. Development of Electronic Scanning

In the early 1920's interest in electronic, as opposed to mechanical, scanning began to take form. Although it is beyond the scope of our work to trace the development of the all-electronic television system, it is of interest to note a few highlights in two major branches of the work which were finally combined in 1934.

At the beginning of that era, work was carried out at the Radio Corporation of America toward the development of a system that employed the cathode-ray tube as the reproducing element. 1929 marked one of the first receptions of a television image which was reproduced electronically. During the same interval research on an electronic pickup device was also under way but it lagged behind the work on the cathode-ray tube. While Zworykin had conceived of the principle of the iconoscope camera tube, it was not until 1932 that it was developed sufficiently for reporting to the industry. At the time of the 1929 test a mechanical galvanometer was used as the transmitter.[4]

During the same decade members of the staff at Purdue University had been doing work in the design and operation of cathode-ray tubes.[5] Cognizance of this work caused the Grigsby-Grunow Company, which was manufacturing Majestic radio receivers at that time, to contact the University in 1929 with the result that a joint

[1] H. W. Lee, "The Scophony Television Receiver." *Nature*, **142**, 59 (July 9, 1938).

[2] Scophony Television, *Electronics*, **9** (3), 30 (March 1936).

[3] D. M. Robinson, "The Supersonic Light Control and Its Application to Television with Special Reference to the Scophony Television Receiver." *Proc. IRE*, **27**, 483 (August 1939).

[4] V. K. Zworykin, "Television with Cathode-Ray Tube for Receiver." *Radio Engineering* (December 1929).

[5] C. F. Harding, R. H. George, and H. J. Heim, "The Purdue University Experimental Television System." Engineering Bulletin, R.S. No. 65, Engineering Experiment Station, Purdue University, 1939.

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